Short communication

Identification of key events in baseball hitting using inertial measurement units

Niroshan G. Punchihewa [a,c], Go Yamako [b,*], Yuu Fukao [a], Etsuo Chosa [c]

[a] Graduate School of Medicine and Veterinary Medicine, University of Miyazaki, Japan
[b] Department of Mechanical Design Systems Engineering, Faculty of Engineering, University of Miyazaki, Japan
[c] Department of Orthopaedic Surgery, Faculty of Medicine, University of Miyazaki, Japan

ARTICLE INFO

ABSTRACT

Quantification of baseball hitting mechanics under game conditions help players to become successful batters and prevent injuries. Inertial measurement units (IMUs) can measure motion without any spatial restriction and are thus becoming a popular tool to investigate sports biomechanics. Biomechanical analysis of hitting requires the accurate detection of key events including "foot-off" while leaning back (F_{Off}), "foot-on" during forward swing (F_{On}), and ball impact. Ten male university baseball players hit a ball suspended on a T pole five times in kick-hitting and glide-hitting styles. Three IMUs were attached on mid-pelvis and on each hand to record acceleration and orientation data. The key events identified by the three IMUs were compared with those retrieved by an optical motion capture system with force platforms. The timings of the local peak acceleration of the pelvis in the direction of the pitcher that were recorded by the IMU closely matched those of F_{Off} and F_{On} events detected by the ground reaction force. Root mean square error (RMSE) between each measurement for the F_{Off} and F_{On} events were 0.024 and 0.031 s, respectively. The timing of the negative peak of acceleration in the proximal direction of the hands corresponded to the impact time determined by an optical motion capture system. RMSEs for the knob and barrel-side hand were 0.009 and 0.011 s, respectively. Our results demonstrate how IMUs can be useful for analyzing baseball hitting mechanics.

© 2019 Elsevier Ltd. All rights reserved.

1. Introduction

Baseball hitting is considered one of the most difficult sporting actions as batters need to swing the bat in less than half a second once the ball is pitched (Williams and Underwood, 1986). The swing is initiated with the trunk of the batter moving toward the catcher, thereby shifting his weight to the rear leg (Fortenbaugh et al., 2011). Consequently, the front foot is lifted (kick-hitting) or dragged back (glide-hitting). The "foot-off" (F_{Off}) is recognized as the initial event in the baseball bat swing. Then, the batter moves his trunk toward the pitcher to increase momentum by shifting his weight from the back foot to front foot. This stride of forward swing ends with the front foot planted on the ground (F_{On}). The momentum generated by the forward swing is transferred from the bat to the ball through direct contact (Impact). Swing time is taken as F_{On} to Impact event. Biomechanical charac-

teristics change in each phase and F_{Off}, F_{On}, and Impact are recognized as key events in analyzing baseball hitting (Escamilla et al., 2009; Katsumata, 2007; Welch et al., 1995).

Optical motion capture system (OMCS) is the gold standard tool for batting motion analysis. However, a majority of baseball hitting analyses are performed indoors and are limited to hitting off a tee instead of live pitching (Ae et al., 2017; Dowling and Fleisig, 2016; Reyes et al., 2011). Kinematic differences between tee batting and pitched batting has been previously demonstrated (Ae et al., 2018).

The use of an inertial measurement unit (IMU) has recently been expanded into sports movement analysis (Chambers et al., 2015). Recently, in baseball, the importance of IMU has been widely discussed (Fleisig, 2018). Makhni et al. (2018) reported the significance of IMU in baseball pithing. Ghasemzadeh and Jafari (2011) used IMUs for coordination analysis to distinguish between good and bad swings. However, the validity of detecting the key events using IMUs needs to be well documented during baseball hitting. In the present study, we aimed to compare the F_{Off}, F_{On}, and Impact events as detected by IMU with those detected by OMCS under stationary baseball hitting. In addition, we evaluated the effects of the hitting style in identifying foot events.

* Corresponding author at: Department of Mechanical Design Systems Engineering, Faculty of Engineering, University of Miyazaki, 1-1, Gakuen Kibanadai, Nishi, Miyazaki, Japan.

  E-mail address: g.yamako@cc.miyazaki-u.ac.jp (G. Yamako).

2. Methods

2.1. Participants

Ten male collegiate baseball players volunteered and provided informed consent for the study. The study was approved by our institutional ethics committee. The demographic and biographic characteristics of the study participants are as follows: mean age, 20.9 (standard deviation = ±1.1) years; mean body mass, 71.3 (±6.4) kg; and mean height, 172.4 (±5.7) cm. The participants were classified into two groups according to their natural hitting style: kick-hitting (KH) and glide-hitting (GH) groups. After a voluntary warmup, the participants were given five trials per hitting style. The purpose was to hit a ball suspended on a T pole. The first five trials were performed using their natural hitting style. Thereafter, the participants were given time to get accustomed to the other style. A break of not less than 30 s was given to each participant between each swing. The hitting motions for each trial were simultaneously recorded using IMUs and OMCS.

2.2. IMU

Three wireless IMUs (MyoResearch® model 610, Noraxon Inc., Scottsdale, AZ, USA) comprising a tri-axial accelerometer (±157.0 m s^{-2}), tri-axial gyroscope (±2000 deg·s^{-1}), and magnetometer (±1.9 Gauss) were used to measure the acceleration and orientation of pelvis and hands at 200 Hz during the bat swing. The IMUs were attached on the dorsal side of the hands using neoprene tape (Fig. 1a). One was attached directly on the sacrum skin using an elasticized bandage. Local coordinate systems for each IMU were aligned with anatomical landmarks (Fig. 1a). During a bat swing, data from each IMU were stored in a laptop computer connected to a wireless receiver.

2.3. OMCS

This study employed 10 infrared cameras (250 Hz; Vantage-V8, Vicon Motion Systems Ltd., UK) and 2 force platforms (1000 Hz; AMTI, USA). The OMCS was synchronized with IMUs using a pulse trigger. A global coordinate system was established, denoting the landmarks of a baseball field. The Y-axis is oriented from the home plate toward the catcher and the X-axis from the right batter box toward the left batter box, which is orthogonal to the Y-axis. Further, the Z-axis is vertically oriented upward (Fig. 1b). Two markers were attached on the sacrum (Fig. 1a). The center point of the two markers was calculated to analyze the pelvis motion. One marker was attached on the ball to detect the *Impact*.

2.4. OMCS data processing for the identification of the key events

Ground reaction force (GRF) of the front foot and the displacement of the marker on the ball were used to detect the key events based on previous studies. A

fourth-order low-pass Butterworth filter was used to smoothen the GRF (cut-off frequency = 75 Hz). The F_{Off} point was defined as the time when the GRF of the front foot becomes zero (Fleisig et al., 2013; Welch et al., 1995). In the GH style, the local minimum was used when the front foot was not completely lifted off the ground. The F_{On} time was defined as the time when the GRF of the front foot surpassed 50% of a participant's body weight (Laughlin et al., 2016; Fortenbaugh et al., 2011). The relationship between the GRF of the front foot and the pelvis motion was also evaluated. The *Impact* time was defined as the first frame before a ball contacts using the displacement of the marker attached to the ball (Inkster et al., 2011; Katsumata et al., 2017).

2.5. IMU data processing for the identification of the key events

In the detection of F_{Off} and F_{On}, the acceleration of a pelvic sensor (P_S) in the global Y-axis (direction from the batter to the pitcher; Fig. 1b) was used. For the calibration of P_S, the participants stood such that the local y-axis of P_S was parallel to the global Y-axis prior to the trials and was set as zero to the orientation of P_S. Using a rotation matrix constructed from the orientations of P_S (Euler angles) during bat swing, the acceleration data were transformed. Changes in the Y-axis acceleration of the P_S were processed to detect the F_{Off} and F_{On} events (Fig. 2). Further, data were smoothed to remove high frequency components and the peaks were amplified using the Gaussian convolution filter (window size = 10). The F_{Off} time was defined as the first positive peak in the acceleration. The F_{On} time was defined as the time when the acceleration reached a minimum value.

Regarding *Impact*, the acceleration data of IMUs attached on the knob side (KS) and barrel side (BS) of the hands were smoothed using a fourth-order, zero-lag, low-pass Butterworth filter (cut-off frequency = 15 Hz). The *Impact* was defined as the time when acceleration reached a negative peak, which was detected using the rate of change in acceleration calculated using central difference method for differentiation from the acceleration data (Winter, 2009).

2.6. Statistical analysis

A total of 99 hitting trials (KH = 49, GH = 50) were analyzed to detect the key events. One trial was excluded due to recording error in IMU. Statistical analyses were performed using SPSS version 21.0 (IBM corp., Tokyo, Japan). We compared the key events detected by IMU and OMCS. Agreements for each event were quantified using root mean square error (RMSE) and intraclass correlation coefficient (ICC; a two-way mixed model for absolute agreement). The time differences for each foot event between the KH and GH style were compared using Mann–Whitney U test. In addition, the time difference for *Impact* was also compared between KS and BS hand. $P < 0.05$ was considered statistically significant.
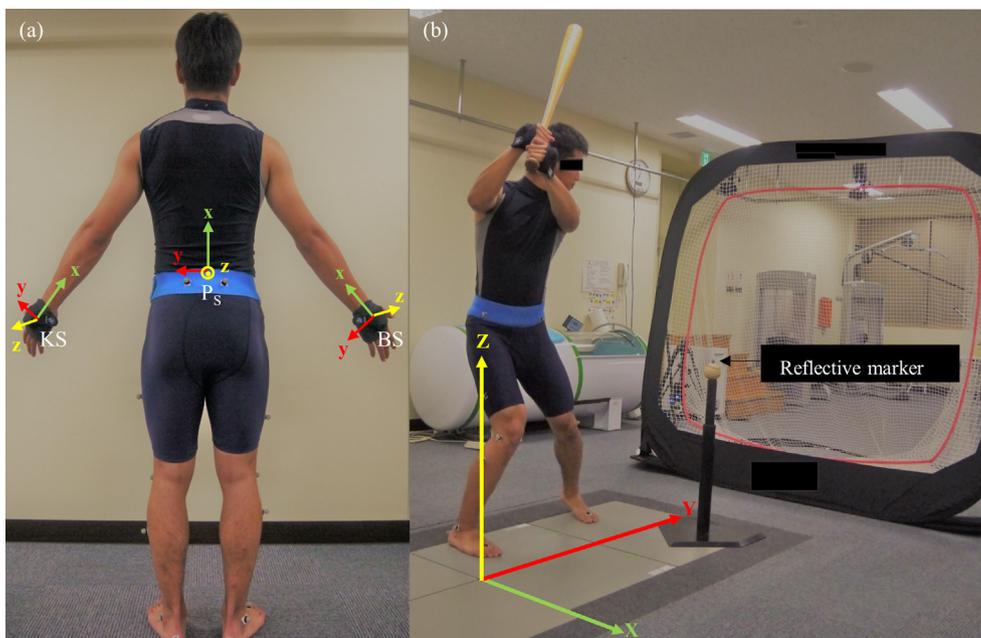
Fig. 1. (a) Sensor placement and local coordinate system in a right-handed batter. (b) Optical motion capture system and global coordinate system. The front and rear foot are placed on the force plates. A baseball with a reflective marker is placed on a T pole. The Y-axis is the direction from the home plate to a pitcher. The X-axis is the direction from the right to left batter box. The Z-axis is vertically upward. Abbreviations: P_S, pelvis sensor; KS, knob-side sensor; BS, barrel-side sensor.
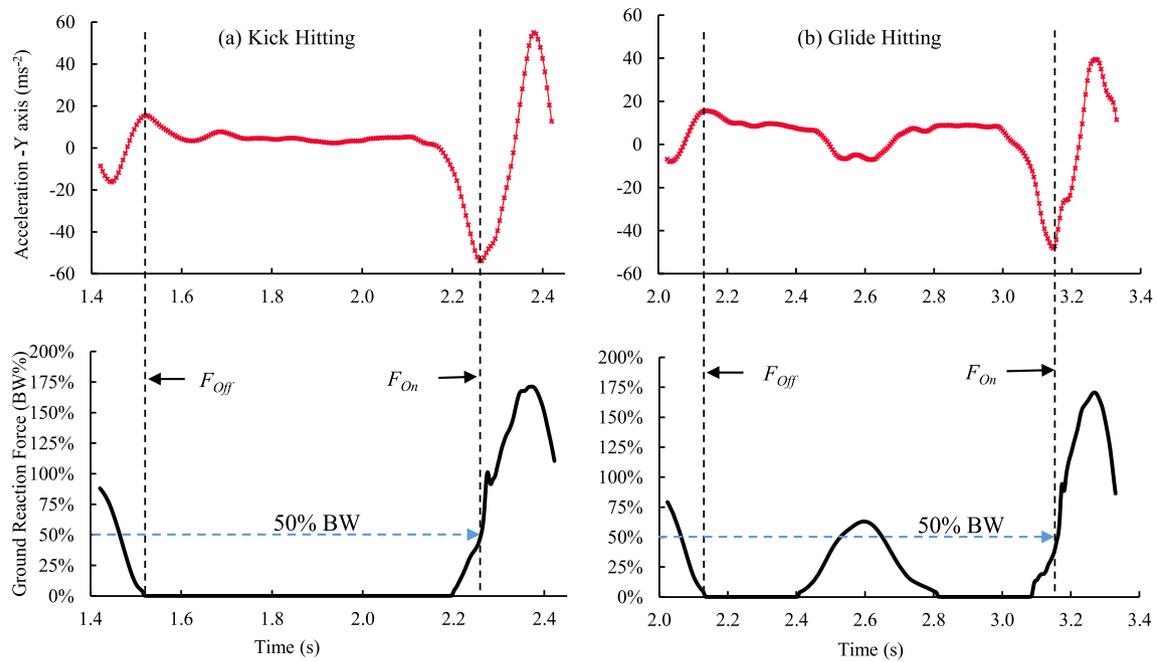
Fig. 2. Typical example of acceleration data detected by the pelvis sensor and ground reaction force of the front foot in (a) kick-hitting and (b) glide-hitting styles. Abbreviations: F_{Off}, foot-off; F_{On}, foot-on; BW, Body weight.

3. Results

3.1. F_{Off} and F_{On} event

For both hitting styles, P_S detected local peaks in acceleration along the Y-axis (along the pitcher's direction) for the F_{Off} and F_{On} events (Fig. 2). Excellent agreements between IMU and OMCS were observed (ICCs > 0.99, Table 1). In F_{Off} time, the RMSE was 0.024 s for the KH and GH style. For F_{On} time, RMSEs were 0.032 and 0.029 s for KH and GH, respectively. When the hitting styles were compared, F_{Off} was detected more accurately for the GH style than for the KH style ($p < 0.001$).

After F_{Off}, the pelvis was moved gradually in positive Y-axis and reached the peak at F_{On}, and then reversed until *Impact* (Fig. 3). The F_{On} time coincided with the local peak of the pelvis position (Table 2).

3.2. Impact event

For KS and BS hand IMUs, oscillations in acceleration were observed for each axis at the *Impact* (Fig. 4). The time for minimum acceleration along the local x-axis corresponded to the *Impact* detected by OMCS (ICCs = 1.00). RMSEs of the KS and BS hand were 0.009 and 0.011 s, respectively ($p = 0.001$, Table 1).
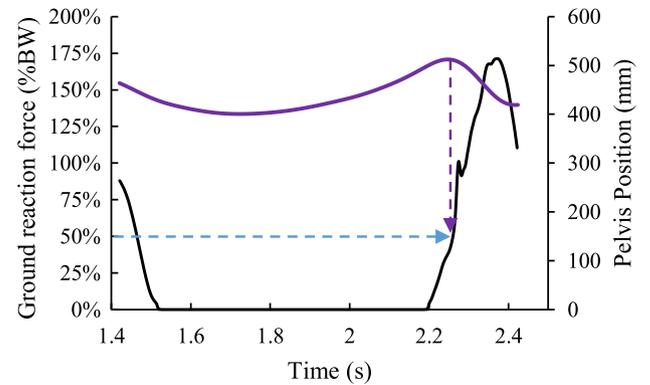
Fig. 3. Relationship between front foot ground reaction force with the pelvic motion toward the pitcher's direction (Y-axis).

4. Discussion

Baseball hitting analysis requires accurate identification of the key events. Through this study, we demonstrated excellent agreement (ICCs > 0.99) between IMU and OMCS in detecting events, and we showed that the time differences were within 0.032 s for foot events and 0.009 s for the impact under tee-batting condition. The time difference was relatively low compared with the swing

Table 1
Mean time difference (Mean), Standard Deviation (SD), Root mean square error (RMSE) and Intraclass correlation coefficient (ICC) between inertial measurement unit and optical motion capture system at each key event. CI = Confidence Intervals.

Event	Hitting Style	Mean (SD) (s)	RMSE (s)	ICC (CI, 95%)
Foot Off	Overall	0.005 (0.024)	0.024	0.999 (0.998, 0.999)
	Kick Hitting	0.014 (0.019)	0.024	0.999 (0.996, 1.000)
	Glide Hitting	−0.004 (0.024)	0.024	0.999 (0.998, 0.999)
Foot On	Overall	0.006 (0.030)	0.031	0.999 (0.998, 0.999)
	Kick Hitting	0.008 (0.032)	0.032	0.998 (0.997, 0.999)
	Glide Hitting	0.005 (0.029)	0.029	0.999 (0.998, 0.999)
Impact (KS)	Overall	0.000 (0.009)	0.009	1.000 (1.000, 1.000)
Impact (BS)	Overall	−0.004 (0.011)	0.011	1.000 (1.000, 1.000)

Table 2
Mean time difference (Mean), Standard deviation (SD), Root mean square error (RMSE) and Intraclass correlation coefficient (ICC) between ground reaction force at 50% body weight and front most pelvis position to the pitcher's direction. CI = Confidence Intervals.

Hitting style	Mean (SD) (s)	RMSE (s)	ICC (CI, 95%)
Overall	0.000 (0.053)	0.053	0.996 (0.994, 0.997)
Kick Hitting	0.008 (0.059)	0.059	0.995 (0.991, 0.997)
Glide Hitting	−0.008 (0.047)	0.047	0.997 (0.995, 0.998)
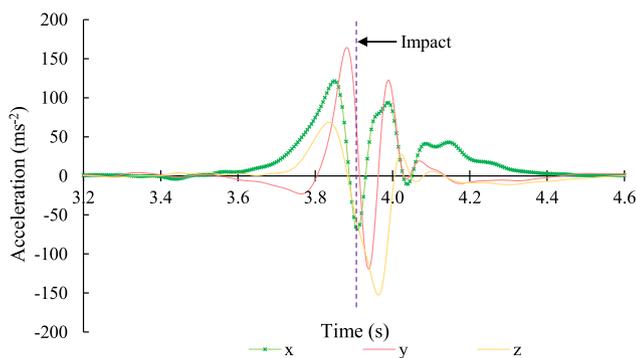
Fig. 4. Typical example of acceleration data detected by knob-side inertial measurement unit. Dash line indicates the time at impact detected by the optical motion capture system.

time (range: 0.166–0.201 s) reported in previous studies (Laughlin et al., 2016; Fortenbaugh et al., 2011). The mean swing time detected from IMUs in the current study was 0.163 s.

Using the acceleration changes of the P_S in the direction of the pitcher, the foot events could be detected. The trunk movement toward the pitcher (Y-axis) is important to adjust the bat swing to different pitching speeds (Tago et al., 2017). The propulsive and breaking forces in the back and front foot during bat swing have a significant effect on movement of the body's center of mass (Fortenbaugh et al., 2011; Katsumata, 2007). In this study, we confirmed that F_{On} time coincided with the local peak of pelvis displacement in the Y-axis. Thus, we expected that the pelvis movement toward the pitcher would indicate the foot events.

In KS and BS sensors, the local x-axis acceleration could detect the *Impact*. The x-axis was approximately opposite to the impact direction in KS and BS hand. The IMU on the KS hand was a good detector for the *Impact*. Some batters release the grip of the BS hand toward the end of the swing; thus, the gripping strength may cause differences in acceleration during the *Impact* (Ae and Koike, 2011). The same approach to detect *Impact* was reported using IMU attached on a bat knob (King et al., 2012).

Several limitations of this study should be addressed. During *Impact*, the acceleration would go beyond the measurement range for IMUs. In addition, it was difficult to directly capture the impact time at the sampling rate of 200 Hz because the impact duration is less than 1.5 ms (Cross, 1998). Therefore, we used the central difference method to estimate the peak time of acceleration. A higher sampling rate over 1000 Hz and wider range of acceleration (over 24 G) could improve the detection accuracy of the impact (Adair, 2002). Next, the skin creates artefacts of the hand sensors and errors are induced for detecting the impact. However, it is difficult to fully secure the hand sensors with tape because this would reduce the strength of the bat gripping. Moreover, our study was limited to hit a ball off of a tee. Hitting a stationary ball is different than hitting a pitched ball in terms of perception-action coupling (Ranganathan and Carlton, 2007). Further validation is required

to use the proposed methodology using IMUs on the field under live pitching.

In conclusion, this study demonstrated adequate validity of detecting the key events using IMUs attached to the pelvis and the hands under tee-batting condition. Thus, IMU seems a valid tool to investigate baseball hitting motion for improving performance and preventing injuries.

Conflict of interest disclosure

None.

References

Adair, R.K., 2002. The Physics of Baseball. Harper Collins, New York, NY.
Ae, K., Koike, S., 2011. Kinetic analysis of each hand in baseball batting motion at different hitting point heights. ISBS - Conference Proceedings Archive, Porto, Portugal.
Ae, K., Koike, S., Fujii, N., Ae, M., Kawamura, T., 2017. Kinetic analysis of the lower limbs in baseball tee batting. Sport. Biomech. 16, 283–296.
Ae, K., Koike, S., Fujii, N., Ae, M., Kawamura, T., Kanahori, T., 2018. A comparison of kinetics in the lower limbs between baseball tee and pitched ball batting. Hum. Mov. Sci. 61, 126–134.
Chambers, R., Gabbett, T.J., Cole, M.H., Beard, A., 2015. The use of wearable microsensors to quantify sport-specific movements. Sport. Med. 45, 1065–1081.
Cross, R., 1998. The sweet spot of a baseball bat. Am. J. Phys. 66, 772–779.
Dowling, B., Fleisig, G.S., 2016. Kinematic comparison of baseball batting off of a tee among various competition levels. Sport. Biomech. 15, 255–269.
Escamilla, R.F., Fleisig, G.S., DeRenne, C., Taylor, M.K., Moorman, C.T., Imamura, R., Barakatt, E., Andrews, J.R., 2009. A comparison of age level on baseball hitting kinematics. J. Appl. Biomech. 25, 210–218.
Fleisig, G.S., 2018. Editorial commentary: changing times in sports biomechanics: baseball pitching injuries and emerging wearable technology. Arthrosc. J. Arthrosc. Relat. Surg. 34, 823–824.
Fleisig, G.S., Hsu, W.K., Fortenbaugh, D., Cordover, A., Press, J.M., 2013. Trunk axial rotation in baseball pitching and batting. Sport. Biomech. 12, 324–333.
Fortenbaugh, D., Fleisig, G., Onar-Thomas, A., Asfour, S., 2011. The effect of pitch type on ground reaction forces in the baseball swing. Sport. Biomech. 10, 270–279.
Ghasemzadeh, H., Jafari, R., 2011. Coordination analysis of human movements with body sensor networks: a signal processing model to evaluate baseball swings. IEEE Sens. J. 11, 603–610.
Inkster, B., Murphy, A., Bower, R., Watsford, M., 2011. Differences in the kinematics of the baseball swing between hitters of varying skill. Med. Sci. Sports Exerc. 43, 1050–1054.
Katsumata, H., 2007. A functional modulation for timing a movement: a coordinative structure in baseball hitting. Hum. Mov. Sci. 26, 27–47.
Katsumata, H., Himi, K., Ino, T., Ogawa, K., Matsumoto, T., 2017. Coordination of hitting movement revealed in baseball tee-batting. J. Sports Sci. 35, 2468–2480.
King, K., Hough, J., McGinnis, R., Perkins, N.C., 2012. A new technology for resolving the dynamics of a swinging bat. Sport. Eng. 15, 41–52.
Laughlin, W.A., Fleisig, G.S., Aune, K.T., Diffendaffer, A.Z., 2016. The effects of baseball bat mass properties on swing mechanics, ground reaction forces, and swing timing. Sport. Biomech. 15, 36–47.
Makhni, E.C., Lizzio, V.A., Meta, F., Stephens, J.P., Okoroha, K.R., Moutzouros, V., 2018. Assessment of elbow torque and other parameters during the pitching motion: comparison of fastball, curveball, and change-up. Arthrosc. J. Arthrosc. Relat. Surg. 34, 816–822.
Ranganathan, R., Carlton, L.G., 2007. Perception-action coupling and anticipatory performance in baseball batting. J. Mot. Behav. 39, 369–380.
Reyes, G.F., Dickin, D.C., Crusat, N.J.K., Dolny, D.G., 2011. Whole-body vibration effects on the muscle activity of upper and lower body muscles during the baseball swing in recreational baseball hitters. Sport. Biomech. 10, 280–293.
Tago, T., Kaneko, K., Tsuchioka, D., Ishii, N., Wada, T., 2017. Influence of the ball speed on the displacement of the center of gravity during baseball batting motion. In: ISBS Proceedings Archive, Cologne, Germany, pp. 245–248.
Welch, C.M., Banks, S.A., Cook, F.F., Draovitch, P., 1995. Hitting a baseball: a biomechanical description. J. Orthop. Sports Phys. Ther. 22, 193–201.
Williams, T., Underwood, J., 1986. The Science of Hitting. Simon & Schuster.
Winter, D.A., 2009. Biomechanics and Motor Control of Human Movement. John Wiley & Sons Inc, Hoboken, NJ, USA.